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MECHANICAL PROPERTIES OF PRESERVATIVE TREATED MARINE PILES - RE--ETC(U)

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author: Max L. Eaton, Joseph A. Drelicharz, and Thorndyke Roe, Jr.

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1. Wood piling – destructive testing 2. Preservative treatment I. YF54.593.012.01.005

Forty southern pine and thirty-five Douglas fir piles were destructively tested at the Forest Research Laboratory, Corvallis, Oregon. The forty southern pine piles represent eight different preservative treatments (including one lot untreated), five replicates each. One of these treatments was omitted for Douglas fir. The findings were, in general, a reduction in desirable wood characteristics stemming from preservative treatments; in particular, more reduction for dual treatment than for creosote. This, with the higher cost of dual treatment, suggests that before dual treatment can be recommended, it will require evidence of materially greater longevity for the use and environment intended.

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INTRODUCTION

Wood is a very flexible and versatile material: very resistant to the physical and chemical environment but subject to attack by biological agents - fungi, termites, and marine borers. Resistance to these agents can be improved markedly by impregnating the wood with certain toxic compounds or mixtures, which, collectively, are called wood preservatives. Treatment with some of these preservatives is said to produce little change in the physical properties of wood. However, treatment with certain water soluble salts, particularly in dual treatment where the salt treatment is followed by kiln drying and treatment with creosote, has been reported to cause an increase in brittleness in the treated wood. For example, the Naval Reserve Training Center, Wilmington, N.C., reported that of nine 55-foot fender piles received, three arrived cracked or broken, and one broke in two during unloading. Others have stated that the salt treatment alone does not affect the physical properties of the wood, but rather the salt treatment plus the kiln drying used in the dual treatment procedure. Despite this controversy, the American Wood Preservers' Association recommends dual treatment or a 2.5 lb/cu ft salt treatment for piles which are to be driven in areas of severe marine borer hazard. Studies conducted by the Civil Engineering Laboratory (CEL) at Coco Solo, C.Z.* have shown the superiority of dual-treated piles to creosote-treated piles in resistance to marine borers. However, because the major use for wood piles in the Navy is now for fender piles, any significant loss in strength of treated wood becomes very important to the design and maintenance of these energy-absorbing systems.

Thus, CEL was requested to investigate the effects of various commercial treatments on the mechanical properties of wood. It is the purpose of this report to describe and discuss an experiment in which seventy-five piles treated in various ways were destructively tested.

DESIGN OF EXPERIMENT

Thirty-five peeled Douglas fir logs as nearly alike as feasible were selected from on-hand supplies and cut into pieces approximately 30 feet long, nominally 12 inches in diameter at the butt end and 7 inches in diameter at the tip end. These were separated into seven lots of five piles each. The seven different lot treatments were:

*Civil Engineering Laboratory. Technical Note N-1466: 1976 inspection of experimental treated piling, by T. Roe, Jr. Port Hueneme, Calif., Dec 1976.

1. Untreated
2. Standard creosote treatment
3. ACA*, 2.5 lb/cu ft of sapwood
4. ACA, 1 lb/cu ft of sapwood, followed by kiln drying, followed by standard creosote treatment
5. ACA, 1 lb/cu ft of sapwood, followed by air drying, followed by standard creosote treatment
6. CCA*, 1 lb/cu ft of sapwood, followed by kiln drying, followed by standard creosote treatment
7. CCA, 1 lb/cu ft of sapwood, followed by air drying, followed by standard creosote treatment.

All preservative retentions met the minimum American Wood Preservers' Association requirements except for the dual-treated CCA + creosote, both air- and kiln-dried (see Table 1).

Forty peeled southern pine logs as nearly alike as feasible were selected from on-hand supplies and cut into forty pieces approximately 30 feet long, 12 inches in diameter at the butt end, and 7 inches in diameter at the tip end. These were separated into eight lots of five piles each. Seven lots were given the same levels of treatment as the seven lots of fir. An eighth treatment - 2.5 lb of CCA/cu ft of sapwood - was used on the remaining eighth lot. All preservative retentions met the minimum American Wood Preservers' Association requirements.

The 75 piles were then destructively tested at the Forest Research Laboratory, Corvallis, Ore., in a random chronological manner. Table 2 lists the types of test, descriptions of which appear in the next section of this report.

The foregoing experimental design contains several factorial designs which the reader can discern; for example: (1) 70 piles constitute a two-factor experiment (namely, wood at two levels and treatments at seven levels); (2) 40 piles constitute a three-factor experiment (namely, wood at two levels, salt at two levels, and method of drying - after salt, but before creosote - at two levels); and (3) some comparisons are limited either to fir or pine.

To be found in the Appendix are: (1) the six elements of data for each pile; (2) a set of statistical analyses of variance of the data for main and interaction effects with tests of significance; (3) a list of bounds for 0.95 confidence intervals and best estimates of mean differences between various treatment effects; and (4) because salt-treated piles cost more money than those not salt-treated, some additional analyses and confidence intervals for differences on a per dollar basis.

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*ACA, ammoniacal copper arsenite; CCA, chromated copper arsenate.

PILE DESTRUCTIVE TEST PROCEDURES

Bending Tests of Full-Sized Piles

Piles were selected randomly for testing. They were loaded into a 600,000-lb capacity, universal testing machine from the Civil Engineering Department of Oregon State University. If a pile was curved, it was rotated before the loading procedure until there was no horizontal curve. The loading heads, spaced as shown in Figure 1, were loaded until they almost touched the pile, load and deflection recording devices were zeroed, and circumferences were measured at the tip, middle, and butt of each pile. Moisture contents of untreated or creosote-treated piles were measured with a resistance-type moisture meter near a loading head at a depth of 0.5, 1, 1.5, 2, and 2.5 inches.

Data were recorded in two ways: (1) by means of a strip chart attached to the universal testing machine and written data sheets, and (2) a magnetic tape, digital recorder and microphone provided by CEL. The tape reel number, tape footage, date, time, and specimen numbers were recorded on the data sheet, and the tape recorder was set for recording. The specimen number, date, and weather report were spoken into the microphone, and some sounds were recorded of the breaking piles. The loading rate was 0.53-in./min until failure when the head speed was increased until 10 inches of deflection occurred. Maximum breaking load (P_{max}) was recorded on the data sheets as were abnormalities such as severe slope of grain or overabundance of knots, and the type of failure (i.e., compression, tension, or shear).

After these bending tests, a 4-ft-long butt specimen and a 3-in.-long cross section near the failure were cut from each pile. The 4-ft-long specimens were sent to CEL and the 3-in.-long sections were saved for preservative analyses. Moisture content specimens were taken near the point of failure. Salt-treated and untreated specimens were oven-dried. The Karl Fischer method was used to determine moisture contents of creosote and salt-treated specimens. Sections of piles from the vicinity of failure points were cut and saved.

Compression Tests on Piles Segments

The 4-foot butt specimens obtained earlier were squared off with a table chainsaw to a length of 45 inches. The specimens were submerged in water in a retort and 90 psi of pressure applied to bring the wood to its fiber saturation point. This water-impregnation treatment required 1 day for pine and 1 week for Douglas fir. Moisture contents of creosoted specimens were recorded with five readings at 1/2-inch-depth increments up to a total depth of 2-1/2 inches in the middle of a piece 2 feet from its end. The moisture content of dual-treated piles was assumed to be similar to creosote-treated material. The moisture content of salt-treated piles was assumed to be similar to the untreated specimens. The average moisture contents after pressure treatment with water were 30% for southern pine and 28% for Douglas fir.

The length and circumference at butt and tip of each specimen was measured. Loading to failure was at the rate of 200 kips/min. The location of each failure was recorded.

Findings

All the findings in Table 3 are relative to and limited to the treatments (e.g., quantities of salts), type of pile, and methods of testing described in the Design of Experiment and Pile Destructive Test Procedures sections.

For all these reported differences (reductions relative to untreated piles, relative to creosoted piles, and any comparison indicated in Table 3), the best estimates of predicted amount of change are contained in the Appendix (Tables 18, 19, and 20), together with 0.95 confidence bounds for each difference. The reader should note that those cases are not listed in Table 3 findings where the confidence region for the differences contain zero (i.e., bounds of opposite algebraic sign).

Table 3 contains 96 findings. Because each of these was based on the 0.95 level of significance, the expected number of erroneous findings is less than 4.8 (5% x 96). Just which findings are false is not known. For the convenience of the reader, Table 4 is shown. The entries in the table are merely the average (mean) of the 5 (or 10, or 20) test results. Entries not related to the findings are omitted.

Shortage of funds precluded the seeking of findings for E_c and μ_c.

DISCUSSION

Tables 4, 5, and 6* may be useful to the designer and planner. Data on strength of piles found in handbooks usually refer to untreated piles. A designer can obtain from Table 4 a rough estimate of the ratio of strength for his choice of species and treatment compared to that of the stronger untreated piles. Then the number of piles required for the job can be estimated.

The planner, in deciding between alternative treatments, may make use of these tables. For example, if creosoted fir bearing piles and CCA dual-treated fir bearing piles are the choices, Tables 5 and 6 in the Appendix show an average F_c of 3,200 psi for creosoted fir; Table 4, 2,333 psi for CCA dual. Comparative costs, which can be found in the Appendix, are, respectively $5.50 and $6.50/linear ft.

$$\frac{3200}{5.5} \div \frac{2333}{6.5} = 1.621$$

*Tables 5 and 6 are found in the Appendix.

Thus, it is estimated that to obtain equivalent bearing support for the pier it will cost 62% more dollars if the dual treatment rather than creosote is chosen. This can be justified if the dual-treated piles will last more than 1.62 times the longevity (in years) of creosoted piles in the application and environment intended.

Admittedly, this is a very rough computation for many reasons, such as:

(1) Cost of installation and inflation are ignored.

(2) Table values are based on a limited number of piles, selected originally for high quality appearance and apparent low variation from pile to pile. Thus, the table values may be higher than they would be if unselected run-of-the-mill piles were used.

(3) Tables 5 and 6 data are not moisture corrected. They are, however, representative of what the planner might find in the storage yard and thus representative of recently driven piles before moisture saturation. Rate of moisture absorption is not known by the authors.

(4) The reduced strength increases the frequency of reinstallation and this is ignored.

Because it is difficult to estimate <u>a priori</u> how long a pile of a particular species, treatment, use, and environment will last before need for replacement, an economical field test is suggested. Briefly, this would consist of selecting at random from the list of competitive treatments a replacement pile for each and every pile needing replacement. If records were kept on all these replacements relative to costs, dates of installation and replacement, location, and other data, after a number of years analysis of the data should bring to light the best choice.

CONCLUSIONS

For Douglas fir piles, it is concluded that:

(1) Dual treatment (ACA and creosote or CCA and creosote) or treatment with only ACA will reduce some mechanical properties of a pile more than treatment with creosote. For specific numerical reduction refer to Table 4.

(2) Of the two dual treatments, CCA and creosote reduces some mechanical properties of a pile more than ACA and creosote (refer to Table 4).

(3) In dual treatments, kiln drying is more deleterious than air drying (refer to the Appendix).

For southern pine piles, it is concluded that:

(1) Dual treatment (ACA and creosote or CCA and creosote) or treatment with ACA only are more deleterious to more mechanical properties than treatment with creosote (refer to Table 4).

RECOMMENDATIONS

It is recommended that:

(1) In areas where piles are destroyed mainly by mechanical means, creosote-treated piles should be considered.

(2) In areas where piles are destroyed mainly by biological attack and it is known that dual-treated piles will last sufficiently longer than creosoted piles, the additional expense will be justified.

(3) Accurate records should be kept of randomly placed pile treatments and of installation and removal dates so that a better selection of treatments could be made.

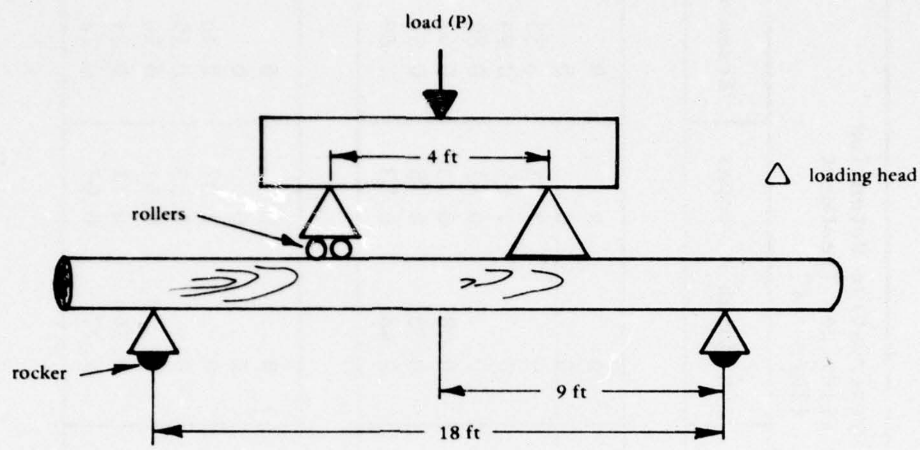

Figure 1. Testing apparatus diagram.

Table 1. Preservative Retention of Marine Piles Within a 1-Inch Depth

Treatment		Specific Gravity	Average Preservative Retention of Five Piles per Treatment (lb/cu ft)				
No.	Type		Creosote	Total Salt	Chromium	Copper	Arsenic
Southern Pine							
1.	Untreated	0.54	0	0	0	0	0
2.	Creosote	0.54	28.9	0	0	0	0
3.	ACA	0.54	0	6.76	0	3.43	3.33
4.	ACA, kiln, creosote	0.53	29.8	2.04	0	1.05	0.99
5.	ACA, air, creosote	0.55	29.5	1.70	0	0.81	0.89
6.	CCA, kiln, creosote	0.54	27.6	1.58	0.68	0.23	0.67
7.	CCA, air, creosote	0.55	31.1	1.39	0.63	0.18	0.57
8.	CCA	0.56	0	5.18	2.46	0.83	1.89
Douglas Fir							
1.	Untreated	0.47	0	0	0	0	0
2.	Creosote	0.44	21.6	0	0	0	0
3.	ACA	0.44	0	4.67	0	2.37	2.30
4.	ACA, kiln, creosote	0.46	30.6	1.12	0	0.53	0.59
5.	ACA, air, creosote	0.46	30.5	1.05	0	0.51	0.54
6.	CCA, kiln, creosote	0.44	18.7	0.79	0.36	0.12	0.31
7.	CCA, air, creosote	0.46	16.1	0.55	0.27	0.07	0.22

Table 2. Types of Tests

Type of Test	Abbreviation	Units
Flexure:		
Modulus of Rupture	MOR	lb/sq in.
Modulus of Elasticity	E_f	million lb/sq in.
Energy Absorption	μ_f	in.-lb/cu in.
Compression:		
Modulus of Rupture	F_c	lb/sq in.
Modulus of Elasticity	E_c	million lb/sq in.
Energy Absorption	μ_c	in.-lb/cu in.

Table 3. Effect of Treatments on Flexural and Compressive Properties of Piles

Treatment	Properties Reduced[a]	Comment
Fir and Pine Piles Equally Represented[b]		
Creosote, ACA dual, CCA dual, or ACA	MOR, E_f, and μ_f	--
ACA dual, CCA dual, or ACA	F_c	--
Creosote or CCA dual	MOR/\$, μ_f/\$, and F_c/\$	
CCA dual	MOR, E_f, F_c, MOR/\$, F_c/\$	Reduced more than creosote treatment
ACA dual	F_c	Reduced more than creosote treatment
CCA dual	MOR and E_f	Reduced more than ACA dual treatment
Fir Piles		
Creosote, ACA, ACA dual, or CCA dual	MOR, E_f, μ_f, MOR/\$, μ_f/\$, and F_c/\$	--
ACA, ACA dual, or CCA dual	F_c	--
CCA dual	MOR, E_f, F_c, MOR/\$, and F_c/\$	Reduced more than creosote treatment
ACA	μ_f, F_c, MOR/\$, μ_f/\$, and F_c/\$	Reduced more than creosote treatment
CCA dual + kiln drying	E_f and F_c	Reduced more than with air drying

continued

Table 3. Continued

Treatment	Properties Reduced[a]	Comment
Fir Piles (continued)		
Averaged CCA dual and ACA dual + kiln drying	E_f	Reduced more than with air drying
CCA dual	MOR, E_f, and MOR/$	Reduced more than ACA dual treatment
Pine Piles		
ACA dual, CCA dual, ACA, or creosote	MOR	--
ACA dual, CCA dual, or ACA	E_f	--
ACA dual or CCA dual	μ_f	--
Creosote, CCA or CCA dual	MOR/\$, μ_f, and F_c/$	--
CCA dual	MOR/$ and F_c/$	Reduced more than creosote treatment

[a]As a result of the treatment.

[b]For the treatments for which prices were available, pine had a higher F_c/$ than fir.

Table 4. Average of Mechanical Properties of Piles[a]

Type of Treatment	No. of Test Piles	Flexural Properties			Compressive Strength F_c (psi)
		MOR (psi)	E_f (10^6 psi)	μ_f (in.-lb/cu in.)	
Fir and Pine Equally					
Untreated	10	8,201	1.932	5.789	3,308
Creosote	10	6,406	1.597	3.819	-
ACA dual	20	5,418	1.553	2.944	2,935
CCA dual	20	4,006	1.306	2.888	2,878
ACA	10	5,577	1.477	3.312	2,824
Fir					
Untreated	5	8,394	1.922	6.338	3,346
Creosote	5	6,862	1.584	4.202	-
ACA dual	10	6,111	1.537	3.059	2,714
CCA dual	10	3,844	1.171	3.364	2,333
ACA	5	5,620	1.416	2.078	2,462
Pine					
Untreated	5	8,007	1.942	5.240	-
Creosote	5	5,950	-	-	-
ACA dual	10	4,725	1.568	2.829	-
CCA dual	10	4,167	1.441	2.413	-
ACA	5	5,534	1.538	-	-
CCA	5	5,410	-	-	-

[a]Values not included are those that did not lead to significant differences, reported in Table 3.

Appendix

STATISTICAL ANALYSIS OF DATA

The raw data stemming from the testing at Forest Products Laboratory, Corvallis, Ore., is contained in Tables 5 and 6. Perusing these tables, the reader will note the large variations among the five replicates (quintuplicates of common property and common treatment) in most of the cells. So, when a difference is noted between the means (averages) of two different treatments, how can one be sure that this difference was caused by the treatment and not by the vagaries of chance stemming from the large natural variation from pile to pile? The answer is that one cannot be sure; however, one can analyze the data, making a test of significance, and then refusing to draw a conclusion unless one is sure with 0.95 probability. In the analysis-of-variance summary tables in this Appendix, one asterisk in the F column* means the corresponding main treatment effect (or interaction effect) is real with 0.95 probability; two asterisks, with 0.99 probability; and three asterisks, with 0.999 probability.

First, a complete analysis of variance (Table 7) will be shown for explanation to the reader; and then, to compress the volume of this Appendix, only the results (the F column) for many analyses will be displayed in the several tables to follow. The abbreviations used in these tables in the Appendix are:

Source	Abbreviation	Source	Abbreviation
Wood	W	Treatment	T
Chemical	C	Interactions	
Drying	D	Wood-Chemical	WC
Experimental Error	EE	Wood-Drying	WD
		Wood-Chemical-Drying	WCD
		Wood-Treatment	WT

Let's consider the effect on MOR due to changing wood from pine to fir, changing chemical treatment from ACA and creosote to CCA and creosote, and changing the method of intermediate drying from kiln to air. Forty piles were available for this. Table 7 presents the detailed analysis.

*F (Fisher's F) is a ratio of estimated variances and is used to perform tests of significance following an analysis of variance.

The interpretation is - with virtual* certainty - that in the environment of equal numbers of fir and pine piles and equal numbers of kiln- and air-dried piles, CCA and creosote will reduce MOR more than ACA and creosote will. Further, there is an additional interaction effect on MOR between wood and chemical in that the additional reduction caused by CCA is more pronounced for fir than for pine.

Table 8 relates to the same 40 piles considered in Table 7, but relates to E_f, μ_f, F_c, and E_c additionally, omitting each analysis of variance leading to the computed F column shown. Missing entries in Table 8 are for F values less than unity, where the effect, if any, was hopelessly lost through experimental error. For the convenience of those interested in lower levels of significance, for Table 8, the probability levels and corresponding critical F values are listed as follows:

Probability Level	Critical F Values
0.70	1.11
0.90	2.87
0.95	4.15
0.99	7.50
0.999	13.2

Any computed F value equal or greater than the F associated with a given probability passes the test for that probability.

From Table 8 alone and similar tables in this Appendix, where significant effects are shown by asterisks, it is not possible to learn which treatment caused the greater reduction in mechanical properties, but this information was determined and will be discussed later in the Appendix.

Thirty-five pine piles were given the same set of seven treatments as thirty-five fir piles. Data from these 70 piles were analyzed; the F results can be found in Table 9; and their corresponding critical F values are in Table 10.

Much of the treatment variation in Table 9(a) stems from the presence of 10 untreated piles. Thus Table 9(b) presents the F values when 10 untreated piles were excluded from the 70 piles.

Table 9(c) uses 20 piles to compare fir with pine and creosote only with 2.5 lb/cu ft ACA treatment only. The significant WT interaction for μ_f is of interest: for fir, ACA reduces flexure energy-absorbing capacity more than does creosote; but for pine, creosote does more harm than ACA.

Because kiln drying is disfavored by some, 40 non-kiln-dried piles were used in Table 9(d) to compare four treatments. Table 10 shows probability levels versus corresponding critical F for Table 9.

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*The critical F for 0.999 probability is 13.16 (from statistical tables) and the computed F (Table 7) was 13.69, even greater.

Table 11 presents computed F's for fir piles only. The original 35 fir piles represent seven different treatments. When the 5 untreated fir piles are excluded, the remaining 30 piles represent six different treatments. Table 12 shows the probability levels with corresponding critical F values for the fir piles.

Table 13 presents computed F's for pine piles only. The original 40 pine piles represent eight different treatments. When the 5 untreated pine piles are removed, the remaining 35 piles represent seven treatments. Table 14 shows the probability levels with corresponding critical F values for Table 13.

A careful study of the data indicates generally that creosote or salt reduces the mechanical properties of piles. These treatments also increase the cost of the piles. Available current prices (dollars per foot) of pile are listed in Table 15; prices are based on fir delivery to Port Hueneme, Calif., and pine to Norfolk, Va.

In order to examine MOR, μ_f, and F_c on a dollar basis by comparison of the 12 possibilities (for which prices were available) listed in Table 15, data from Tables 5 and 6 were simply divided by the figures in that table to arrive at data on the random variables MOR/\$, μ_f/\$, and F_c/\$. These data were then analyzed, and Table 16 was developed from the 40 piles available for fir and pine comparison, from the 35 fir piles, and from the 25 pine piles, including and excluding untreated piles. Table 17 presents the probability levels and critical F values for Table 16.

To this point, this Appendix has been nearly limited to tests of significance, which merely point to those areas where conclusions may be found, without spelling out any conclusions. Needed now are statements relative to how much better or poorer one class of piles is than another. Tables 18, 19, and 20 meet this objective.

Because much information will be compressed into these tables, some explanation of the format and meaning may clarify their interpretation. First, the following is a list of abbreviations in alphabetical order used in the tables:

A	ACA
a	Air-dried
C	CCA
F	Fir
K	Creosote
k	Kiln-dried
ℓ	Lower bound of 0.95 confidence interval for mean of R
$\tilde{M}$	Best estimate of mean (average) of the random variable
P	Pine
R	Random variable (in every case, this will be the difference between two treatment effects)
U	Untreated
u	Upper bound of 0.95 confidence interval for mean of R

The second column of Tables 18, 19, and 20 lists the particular random variable. Every random variable listed is a difference; for

example, "K-A,K" means the difference between the random variables associated with creosoted piles and the corresponding random variables associated with ACA and creosote-treated piles with equal numbers of air- or kiln-dried. The number of piles used to obtain the entries in the ℓ, $\tilde{M}$, μ columns appear in the first column. For the example given, where both pine and fir were used, the first column will read 10x20; i.e., 10 creosoted piles versus 20 dual-treated piles. Reference to the experimental design shows just which piles.

The degree of confidence chosen before drawing a conclusion (finding) is with probability 0.95. If one continued this philosophy, in the long run less than 5% of the conclusions will be fallacious. An entry in the $\tilde{M}$ column is the best estimate of the difference of the average of a very large number of piles treated in one manner minus the average of a very large number treated in a second manner. Even though the entry is the best estimate, it is a very poor estimate. To see how poor, one can observe the width of the interval from ℓ to μ. The probability that truth lies someplace between ℓ entry and μ entry is 0.95. Thus, if one abides by this philosophy, a conclusion will not be drawn when the ℓ and μ entries are of opposite algebraic sign. For example, for Douglas fir piles and for μ_f (flexural energy-absorbing capacity in pound-inches per cubic inch), 2.5 lb ACA/cu ft of sapwood will reduce μ_f more than standard creosote treatment. Exactly how much more reduction would be experienced on the average from a very large number of each kind of pile is unknown. The best estimate is 2.1 in.-lb/cu in. With 0.95 probability, the truth lies somewhere between 0.4 and 3.9.

Table 5. Structural Properties of Southern Pine Piles

Identification	MOR (#/in.^{2})	E_f (10^6 #/in.^{2})	μ_f (avg) (in.-#/in.^{3})	F_c (#/in.^{2})	E_c (10^6 #/in.^{2})	μ_c (in.-#/in.^{3})
1.[a] Control (Untreated)						
011	11,800	2.73	10.9	4160	0.972	15.8
012	5,140	1.36	3.0	2540	0.555	9.7
013	8,090	1.63	4.01	3260	0.741	13.8
014	8,340	2.08	3.36	3160	0.775	16.4
015	6,670	1.91	4.93	3230	0.775	16.2
mean	8,008	1.95	5.24	3270	0.764	14.4
s.d.	2,475	0.52	3.25	579	0.148	2.8
2. Creosote						
071	6,810	1.55	3.93	3980	0.960	22.4
072	6,650	1.62	4.71	3380	0.932	12.8
073	6,150	1.67	5.23	3060	0.927	10.2
074	5,260	1.62	1.43	3420	0.801	12.3
075	4,880	1.59	1.88	3580	0.803	12.1
mean	5,950	1.61	3.44	3484	0.885	14.0
s.d.	850	0.04	1.7	335	0.076	4.8

(continued)

[a]Numbers correspond to treatments listed in Table 1.

Table 5. Continued

Identification	MOR (#/in.^{2})	E_f (10^6 #/in.^{2})	μ_f (avg) (in.-#/in.^{3})	F_c (#/in.^{2})	E_c (10^6 #/in.^{2})	μ_c (in.-#/in.^{3})
3. ACA						
051	7,080	1.76	2.78	3540	0.784	15.0
052	6,260	1.54	6.59	3130	0.692	15.6
053	6,070	1.49	6.33	3390	0.819	15.0
054	4,640	1.18	5.13	3020	0.754	11.3
055	3,620	1.72	1.90	2850	0.832	9.7
mean	5,534	1.54	4.55	3186	0.776	13.3
s.d.	1,384	0.23	2.1	279	0.056	2.6
4. ACA, Kiln-Dried, Creosote						
111	6,490	2.21	3.62	3870	1.40	12.6
112	3,620	1.22	3.79	2670	0.737	8.4
113	4,170	1.21	2.66	3060	0.736	11.7
114	4,660	1.70	1.65	3180	0.897	9.2
115	3,940	1.55	2.83	2940	0.818	10.0
mean	4,576	1.58	2.91	3144	0.918	10.4
s.d.	1,135+	0.41	0.86	448	0.278	1.7
5. ACA, Air-Dried, Creosote						
091	5,340	1.72	3.72	3450	1.19	12.9
092	5,200	1.63	1.82	3380	0.868	12.1
093	6,320	1.77	4.11	3390	0.852	9.4
094	5,380	1.50	2.92	3200	0.902	9.6
095	2,130	1.17	1.17	2420	0.692	5.7
mean	4,874	1.56	2.75	3168	0.901	9.9
s.d.	1,597	0.24	1.24	428	0.181	2.8

(continued)

Table 5. Continued

Identification	MOR (#/in.^{2})	E_f (10^6 #/in.^{2})	μ_f (avg) (in.-#/in.^{3})	F_c (#/in.^{2})	E_c (10^6 #/in.^{2})	μ_c (in.-#/in.^{3})
6. CCA, Kiln-Dried, Creosote						
151	5,510	1.70	5.01	3810	1.01	11.9
152	4,290	1.91	0.74	4000	1.16	10.9
153	2,600	1.32	0.94	3100	0.866	7.7
154	2,840	1.19	1.29	3340	0.884	9.3
155	3,590	1.40	2.65	3210	0.944	6.7
mean	3,766	1.50	2.13	3492	0.973	9.3
s.d.	1,179	0.29	1.78	392	0.119	2.2
7. CCA, Air-Dried, Creosote						
131	4,820	1.25	3.76	3520	0.915	11.3
132	5,030	1.45	2.15	3040	0.866	10.0
133	3,790	1.24	2.45	3190	0.940	7.4
134	6,390	1.66	3.10	3820	1.02	10.2
135	2,810	1.29	2.04	3210	0.865	8.5
mean	4,568	1.38	2.70	3356	0.921	9.5
s.d.	1,350	0.18	0.72	313	0.064	1.5
8. CCA						
031	7,970	2.15	5.40	2900	0.811	6.8
032	5,480	1.81	3.66	3860	0.686	18.1
033	6,160	1.86	1.92	4300	0.941	18.0
034	5,470	1.59	3.44	3820	0.725	17.2
035	1,970	1.35	1.33	3970	0.956	17.3
mean	5,410	1.75	3.15	3770	0.824	15.5
s.d.	2,177	0.30	1.6	522	0.123	4.9

Table 6. Structural Properties of Douglas Fir Piles

Identification	MOR (#/in.^{2})	E_f (10^6 #/in.^{2})	μ_f (avg) (in.-#/in.^{3})	F_c (#/in.^{2})	E_c (10^6 #/in.^{2})	μ_c (in.-#/in.^{3})
1.[a] Control (Untreated)						
021	9120	1.86	4.58	3880	0.721	13.0
022	8620	2.01	7.76	3280	0.685	11.3
023	9260	2.08	3.47	3140	0.627	15.0
024	3280	2.09	5.58	3720	0.792	14.9
025	6690	1.57	5.28	2710	0.522	11.3
mean	7394	1.92	5.33	3346	0.669	13.1
s.d.	2519	0.22	1.58	468	0.102	1.8
2. Creosote						
101	7980	1.72	6.23	3570	0.933	13.5
102	7550	1.92	5.80	3710	1.07	11.8
103	6230	1.34	3.22	2870	0.657	11.5
104	5720	1.48	2.11	2820	0.568	11.7
105	6830	1.46	3.65	3030	0.724	13.0
mean	6862	1.58	4.20	3200	0.790	12.3
s.d.	926	0.23	1.75	412	0.206	0.9

(continued)

[a]Numbers correspond to treatments listed in Table 1.

Table 6. Continued

Identification	MOR (#/in.^{2})	E_f (10^6 #/in.^{2})	μ_f (avg) (in.-#/in.^{3})	F_c (#/in.^{2})	E_c (10^6 #/in.^{2})	μ_c (in.-#/in.^{3})
3. ACA						
041	5960	1.46	2.57	2610	0.726	8.6
042	5400	1.36	1.84	2950	0.726	12.5
043	4300	1.19	1.79	2000	0.461	8.4
044	5140	1.49	1.59	2310	0.607	14.7
045	7300	1.58	2.60	2440	0.592	12.0
mean	5620	1.42	2.08	2462	0.622	11.2
s.d.	1113	0.15	0.47	353	0.11	2.7
4. ACA, Kiln-Dried, Creosote						
121	5820	1.60	3.08	3450	0.881	10.7
122	6330	1.28	3.55	2400	0.611	7.5
123	7040	1.56	3.79	3170	0.776	12.1
124	5340	1.46	3.28	2600	0.809	15.7
125	4850	1.29	1.82	2410	0.549	11.0
mean	5876	1.44	3.10	2806	0.725	11.4
s.d.	852	0.15	0.77	477	0.140	3.0
5. ACA, Air-Dried, Creosote						
141	7660	1.84	3.21	2720	0.664	8.8
142	7150	1.50	2.32	2850	0.782	9.6
143	7210	1.88	4.72	3390	0.874	11.2
144	6270	1.91	3.47	2560	0.684	10.2
145	3440	1.05	1.35	1590	0.584	4.4
mean	6346	1.64	3.01	2622	0.718	8.8
s.d.	1701	0.37	1.27	656	0.112	2.6

(continued)

Table 6. Continued

Identification	MOR (#/in.^{2})	E_f (10^6 #/in.^{2})	μ_f (avg) (in.-#/in.^{3})	F_c (#/in.^{2})	E_c (10^6 #/in.^{2})	μ_c (in.-#/in.^{3})
6. CCA, Kiln-Dried, Creosote						
061	2870	1.21	2.75	1160	0.590	4.6
063	4390	1.13	4.82	2080	0.639	5.1
065	3520	0.89	3.15	2690	0.690	9.7
083	3020	0.95	0.79	1930	0.496	6.9
084	3590	0.89	0.96	1540	0.332	5.4
mean	3478	1.01	2.49	1880	0.549	6.3
s.d.	597	0.15	1.67	577	0.141	2.1
7. CCA, Air-Dried, Creosote						
062	5350	1.39	5.80	2920	0.768	11.3
064	3790	1.35	3.12	2980	0.742	9.2
081	4110	1.39	3.67	2900	0.682	10.4
082	3380	1.07	3.12	2420	0.711	6.6
085	4420	1.44	5.46	2710	0.772	8.9
mean	4210	1.33	4.23	2786	0.735	9.3
s.d.	745	0.15	1.3	228	0.038	1.8

Table 7. Analysis-of-Variance Summary for MOR

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F
W	1	2824922	2824922	1.95
C	1	19951562	19951562	13.69***
D	1	3312002	3312002	2.29
WC	1	7301705	7301705	5.05*
WD	1	6502	6502	
CD	1	366734	366734	
WCD	1	36416	36416	
EE	32	46328912	1447778	
TOTAL	39			

Table 8. F Values From Analyses of Variance

Source	Degrees of Freedom	F				
		MOR[a]	E_f	μ_f	F_c	E_c
W	1	1.95	3.32	2.21	28.00***	26.74***
C	1	13.69***	8.90**			
D	1	2.29	1.23	1.68	1.11	
WC	1	5.05*	2.09		5.03*	1.51
WD	1		3.96		2.07	1.67
CD	1			2.61	2.58	
WCD	1				4.65*	1.43
EE	32					
TOTAL	39					

[a]Repeated from Table 7.

Table 9. Computed F Values From Analyses of Variance

Source	DOF	F: MOR	F: E_f	F: μ_f	F: F_c	F: E_c
(a) 70 Piles (35 Fir, 35 Pine)						
W	1	2.62	2.98		29.4***	31.73***
T	6	12.81***	5.98*	4.72*	3.06*	1.61
WT	6		1.17	1.60	3.57**	1.56
EE	56					
Total	69					
(b) 60 Piles, 10 Untreated Piles Excluded						
W	1		4.15*		1.59	31.0***
T	5		3.15*	1.41		1.38
WT	5		1.68	2.37		1.56
Total	59					
(c) 20 Piles (Comparison of Pine With Fir and Creosote Only With 2.5 lb/cu ft ACA Treatment Only)						
W	1	1.05		1.36	10.48**	4.83*
T	1	2.90	2.19		11.09**	5.99*
WT	1			4.92*	2.00	
Total	19					
(d) 40 Piles (Comparison of Four Treatments: Creosote Only; Creosote, Air Dry, ACA; Creosote, Air Dry, CCA; and ACA Only)						
W	1	1.78			18.1***	16.6***
T	3	4.40*	2.88		3.41*	2.85
WT	3	1.07		3.79*		
EE	32					
Total	39					

Table 10. Probability Levels Versus Critical F Values for Table 9

Probability Level	Critical F Values: (a) 70 Piles[a] W	(a) 70 Piles[a] T and WT	(b) 60 Piles[a] W	(b) 60 Piles[a] T and WT	(c) W[a]	(d) 40 Piles[a] W	(d) 40 Piles[a] T and WT
0.70	1.09	1.24	1.10	1.25	1.15	1.11	1.26
0.90	2.80	1.88	2.82	1.98	3.05	2.87	2.27
0.95	4.02	2.26	4.04	2.41	4.49	4.15	2.90
0.99	7.11	3.14	7.19	3.43	8.53	7.50	4.46
0.999	12.1	4.40	12.3	4.95	16.1	13.2	7.05

[a] (a), (b), (c), and (d) refer to Table 9.

Table 11. Computed F Values From Analyses of Variance

Source	Degrees of Freedom	F				
		MOR	E_f	μ_f	F_c	E_c
(a) 35 Fir Piles						
T	6	12.23***	8.59***	5.63***	5.30***	1.91
EE	28					
TOTAL	34					
(b) Fir Piles, Untreated Piles Excluded						
T	5	7.61***	5.32***	2.33	4.35**	2.13
EE	24					
TOTAL	29					

Table 12. Probability Levels Versus Critical F Values for Table II

Probability Level	Critical F Values	
	35 piles	30 Piles[a]
0.70	1.28	1.29
0.90	2.00	2.10
0.95	2.45	2.62
0.99	3.53	3.90
0.999	5.24	5.98

[a]Five untreated piles excluded.

Table 13. Computed F Values From Analysis of Variance

Source	Degrees of Freedom	F				
		MOR	E_f	μ_f	F_c	E_c
(a) 40 Pine Piles						
T	7	3.17*	1.54	1.63	1.29	1.28
EE	32					
TOTAL	39					
(b) Pine Piles, Untreated Piles Excluded						
T	6	1.31		1.28	1.67	
EE	28					
TOTAL	34					

Table 14. Probability Levels Versus Critical F Values for Table 13

Probability Level	Critical F Values	
	40 piles	35 piles[a]
0.70	1.27	1.28
0.90	1.92	2.00
0.95	2.31	
0.99	3.26	

[a]Five untreated piles excluded.

Table 15. Cost of Fir and Pine Piles

Treatment	Cost, $/ft	
	Fir	Pine
Untreated	4.25	4.40
Creosote	5.50	5.50
Creosote, air-dried, ACA	6.78	-
Creosote, kiln-dried, ACA	6.78	-
Creosote, air-dried, CCA	6.50	6.50
Creosote, kiln-dried, CCA	6.50	6.50
ACA	6.27	-
CCA	-	6.80

Table 16. Computed F Values From Analyses of Variance

Source	DOF	F[a] MOR/$	F[a] μ_f/$	F[a] F_c/$
(a) 40 Piles for Comparison of Fir and Pine Piles				
W	1		2.45	10.9**
T	3	126.5***	13.5***	36.4***
WT	3			5.49
EE	32			
Total	39			
(b) 30 Piles (10 Untreated Piles Excluded From Item (a) Above)				
W	1		2.39	30.7***
T	2	41.5***	4.42*	24.4***
WT	2	1.55		6.71**
EE	24			
Total	29			
(c) 35 Fir Piles				
T	6	36.9***	13.5***	21.5***
E	28			
Total	34			
(d) 30 Fir Piles (5 Untreated Piles Excluded From Item (c) Above)				
T	5	11.5***	3.20*	8.41***
EE	24			
Total	29			
(e) 25 Pine Piles				
T	4	10.5***	3.81*	6.58**
EE	20			
Total	24			
(f) 20 Pine Piles (5 Untreated Piles Excluded From Item (e) Above)				
T	3	4.52*	1.31	3.37*
EE	16			
Total	19			

[a] * indicates at least 0.95 probability; **, 0.99 probability; ***, 0.999 probability.

Table 17. Probability Levels Versus Critical F Values for Table 16

Probability Level	Critical F Values: (a) 40 Piles[a] W	(a) 40 Piles[a] T and WT	(b) 30 Piles[a] W	(b) 30 Piles[a] T and WT	(f) 20 Pine Piles[a]
0.70	1.11	1.11	1.12	1.27	1.33
0.90	2.87	2.27	2.93	2.54	
0.95	4.15	2.90	4.26	3.40	
0.99	7.50	4.46	7.82	5.61	
0.999	13.2	6.96	14.0	9.34	

[a] (a), (b), (f) refer to Items (a), (b), and (f) of Table 16.

Table 18. Best Estimates and 0.95 Confidence Bounds, Fir and Pine Piles Equally Represented

Piles	R	MOR			E_f			μ_f			F_c		
		ℓ	$\tilde{M}$	u	ℓ	$\tilde{M}$	u	ℓ	$\tilde{M}$	u	ℓ	$\tilde{M}$	u
35x35	F – P	-119	310	1122	-0.2376	-0.1100	0.0176	-0.5242	0.2511	1.0264	-782	-571	-360
10x10	U – K	634	1795	2956	0.0962	0.3350	0.5738	0.5195	1.4505	3.4205	-429	-34	361
10x20	U – A,K	2281	2783	3284	0.1727	0.3795	0.5863	1.5888	1.2562	4.1101	31	373	715
10x20	U – C,K	3190	4196	5201	0.4192	0.6260	0.8328	1.6443	2.9005	4.1566	88	430	771
25x25	F – P less k	-235	500	1234	-0.1790	-0.0280	0.1230	-0.6782	0.2392	1.1566	-659	-410	-160
20x20	F – P less k,U	-293	528	410	-0.1988	-0.0300	0.1388	-1.0021	0.0235	1.0492	-810	-531	-252
10x10	U – A	1463	2624	3785	0.2162	0.4550	0.6938	1.0265	2.4770	3.9275	89	484	879
10x20	K – A,K	-18	988	1994	-0.1623	0.0445	0.2513	-0.3812	0.8750	2.1312	65	407	749
10x10	K – A	-332	829	1990	-0.1188	0.1200	0.3588	-0.9435	0.5070	1.9575	123	518	913
10x20	A – A,K	-848	158	1164	-0.2823	-0.0755	0.1313	-0.8882	0.3680	1.6242	-453	-111	231
20x20	a – k	-246	576	1397	-0.0773	0.0915	0.2603	-0.5101	0.5155	1.5411	-279	152	431
10x10	A,a,K – A,k,K	-777	384	1545	-0.1498	0.0890	0.3278	-1.5765	-0.1260	1.3245	-475	-80	315
10x10	C,a,K – C,k,K	-394	767	1928	-0.1448	0.0940	0.3328	-0.2935	1.1570	2.6075	-10	385	780
10x20	K – C,K	1395	2400	3406	0.0842	0.2910	0.4978	-0.3256	0.9305	2.1866	122	464	805
20x20	A,K – C,K	591	1412	2234	0.0777	0.2465	0.4153	-0.9701	0.0555	1.0811	-223	56	336
Piles	**R**	**MOR/\$**						**μ_f/\$**			**F_c/\$**		
		ℓ	$\tilde{M}$	u				ℓ	$\tilde{M}$	u	ℓ	$\tilde{M}$	u
20x20	F – P	-139	43	226				-0.0552	0.2382	0.4213	-139	-86	-33
10x10	U – K	499	757	1014				0.3098	0.6468	0.9836	83	158	232
10x10	U – C,a,K	988	1246	1504				0.4708	0.8077	1.1446	218	293	368
10x10	U – C,k,K	1106	1364	1622				0.6488	0.9857	1.3226	277	352	427
10x20	K – C,K	325	548	772				-0.0418	0.2500	0.5417	100	165	230
10x10	C,a,K – C,k,K	-140	118	376				-0.1589	0.1780	0.5149	-16	59	134

Table 19. Best Estimates and 0.95 Confidence Bounds, Fir Piles

Piles	R	MOR			E_f			μ_f			F_c		
		ℓ	$\tilde{M}$	u	ℓ	$\tilde{M}$	u	ℓ	$\tilde{M}$	u	ℓ	$\tilde{M}$	u
5x5	U – K	176	1532	2889	0.0614	0.3400	0.5786	0.3825	2.1360	3.8895	-465	146	757
5x10	U – A,K	1108	2283	3458	0.1438	0.3850	0.6262	1.7604	3.2790	4.7976	103	632	1161
5x10	U – C,K	3374	4550	5726	0.5098	0.7510	0.9922	1.4554	2.9740	4.4926	484	1013	1542
5x5	U – A	1417	2774	4131	0.2274	0.5060	0.7846	2.5065	4.2600	6.0135	273	884	1495
5x10	K – A,K	-424	751	1926	-0.1942	0.0470	0.2882	-0.3756	1.1430	2.6616	-43	486	1015
5x10	K – C,K	1842	3018	4194	0.1718	0.4130	0.6542	-0.6806	0.8380	2.3566	338	867	1396
5x5	K – A	-115	1242	2599	-0.1106	0.1680	0.4466	0.3705	2.1240	3.8775	127	738	1349
10x5	A,K – A	-866	491	1848	-0.1202	0.1210	0.3622	-0.5376	0.9810	2.4996	-277	252	781
10x10	a – k	-359	601	1561	0.0590	0.2560	0.4530	-0.4149	0.8250	2.0649	-71	361	793
5x5	A,a,K – A,k,K	-887	1357	1827	-0.0806	0.1980	0.4766	-1.8435	-0.0900	1.6635	-795	-184	611
5x5	C,a,K – C,k,K	-625	732	2089	0.0354	0.3140	0.5926	-0.0135	1.7400	3.4935	295	906	1517
10x10	A,K – C,K	1307	2267	3227	0.1690	0.3660	0.5630	-1.5449	-0.3050	0.9349	-51	381	813

Piles	R	MOR/$			μ_f/$			F_c/$		
		ℓ	$\tilde{M}$	u	ℓ	$\tilde{M}$	u	ℓ	$\tilde{M}$	u
5x5	U – A	849	1079	1308	0.8428	1.1598	1.4768	292	395	498
5x10	U – C,K	1185	1384	1582	0.6992	0.9738	1.2483	339	428	518
5x5	U – K	498	727	956	0.4103	0.7273	1.0443	102	205	309
5x10	U – A,K	875	1074	1272	0.7655	1.0401	1.3147	298	387	476
5x10	A – A,K	-203	-5	193	-0.3943	-0.1198	0.1548	-97	-8	82
10x10	A,K – C,K	148	310	472	-0.2905	-0.0663	0.1578	-32	41	114
10x10	a – k	-71	91	253	-0.0970	0.1272	0.3514	-17	56	129
5x5	K – A	122	351	580	0.1155	0.4325	0.7496	86	189	292
5x10	K – A,K	148	346	545	0.0382	0.3128	0.5874	92	182	271
5x10	K – C,K	458	656	854	-0.0281	0.2464	0.5210	134	223	312

Table 20. Best Estimates and 0.95 Confidence Bounds, Pine Piles

Piles	R	MOR			E_f			μ_f			F_c		
		ℓ	$\widetilde{M}$	u	ℓ	$\widetilde{M}$	u	ℓ	$\widetilde{M}$	u	ℓ	$\widetilde{M}$	u
5x5	U – K	-6	2058	4122	-0.0654	0.3320	0.7294	-0.5372	1.8040	4.1452	-759	-214	331
5x10	U – A,K	1495	1788	5071	0.0299	0.3740	0.7181	0.3834	2.4110	4.4386	-358	114	586
5x10	U – C,K	2053	3841	5629	0.1569	0.5010	0.8451	0.7994	2.8270	4.8546	-626	-154	318
5x5	U – A	410	2474	4538	0.0066	0.4040	0.8014	-1.6472	0.6940	3.0352	-461	84	629
5x5	U – C	534	2598	4662	-0.2074	0.1900	0.5874	-0.2512	2.0900	4.4312	-1045	-500	45
5x10	K – A,K	-563	1225	3012	-0.3021	0.0420	0.3861	-1.4206	0.6070	2.6346	-144	328	800
5x10	K – C,K	-5	1783	3571	-0.1751	0.1690	0.5131	-1.0046	1.0230	3.0506	-412	60	532
5x5	K – A	-1648	416	2480	-0.2721	0.0720	0.4161	-3.4512	-1.1100	1.2312	-247	298	843
5x5	K – C	-1524	540	2604	-0.5394	-0.1420	0.2554	-2.0552	0.2860	2.6272	-831	-286	259
5x10	A – A,K	-979	809	2597	-0.3471	-0.0030	0.3411	-0.3106	1.7170	3.7446	-442	30	502
5x10	C – C,K	-545	1243	3031	-0.0331	0.3110	0.6551	-1.2906	0.7370	2.7646	-126	346	818
10x10	a – k	-910	1460	2010	-0.3540	-0.0730	0.2080	-1.4495	0.2060	1.8615	-442	-56	330
5x5	A,a,K – A,k,K	-1766	298	2362	-0.4174	-0.0200	0.3774	-2.5032	-0.1620	2.1792	-521	24	569
5x5	C,a,K – C,k,K	-1262	802	2866	-0.5234	-0.1260	0.2714	-1.7672	0.5740	2.9152	-681	-136	433
10x10	A,K – C,K	-902	558	2018	-0.1540	0.1270	0.4080	-1.2395	0.4160	2.0715	-654	-268	118

Piles	R	MOR/$			μ_f/$			F_c/$		
		ℓ	$\widetilde{M}$	u	ℓ	$\widetilde{M}$	u	ℓ	$\widetilde{M}$	u
5x5	U – C	603	1072	1542	0.2058	0.7277	1.2496	82	189	296
5x5	U – K	316	786	1256	0.0443	0.5662	1.0881	3	110	217
5x10	U – C,K	820	1227	1634	0.3677	0.8197	1.2717	124	216	309
5x5	K – C	-183	286	756	-0.3604	0.1615	0.6834	-28	79	186
5x10	K – C,K	34	441	847	-0.1985	0.2535	0.7055	14	107	199
5x10	C – C,K	-252	155	561	-0.3600	0.0920	0.5440	-65	28	120
5x5	a – k	-346	123	593	-0.4336	0.0883	0.6102	-128	-21	86

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